geosciences

Supplementary Materials: Trout Creek Lycopsid Fossil Forest Geology

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Introduction

The Trout Creek lycopsid fossil locality (the "study site") is located in the east central part of Chaffee County, CO, in the central portion of the Mosquito Range in Chubb Park, just west of U.S. Highway 24/285, along the Lenhardy Cutoff on Colorado State Trust Land. U.S. Hwy 24/285 runs through Chubb Park north to south in the study site area from Trout Creek Pass just to the northeast, toward Johnson Village on the southwest. The study site is covered by portions of the Marmot Peak (southeast corner), Antero Reservoir (southwest corner), Castle Rock Gulch (northwest corner), and Buena Vista East (northeast corner) USGS Quadrangle maps (with geologic overlays). The area of the consists of gentle high-rolling hills, where Kaufman Ridge and Limestone Ridge form the significant topographic features to the east and west, respectively, of Chubb Park and trend southeast to northwest, bounding the study site (Figure 1). The Mosquito Range is a relatively straight, narrow mountain range that trends slightly to the west of north. Its narrow crest has been deeply incised by alpine glaciers and has large steep-sided cirques, like the famous Horseshoe Cirque, to the north of the study site. The range is bounded on the west by the Upper Arkansas Valley and on the east by South Park. The range has peaks to the north of the study site rising to over 4200 m (14,000 ft) and Buffalo Peaks to the south of Weston Pass, north of the study site, is a Tertiary volcanic center.

Figure 1. Chubb Park at the study site with its rolling hills extending northward to the Buffalo Peaks Volcanic Complex and Limestone Ridge on the horizon beyond the low meadow-covered ridge.

Most surface deposits are not well exposed in the immediate vicinity of the study site, so many physical attributes, like thickness, stratification, and composition, are taken from observations made at only a few locations. The oldest exposed rocks in the area of the study site are early Proterozoic intrusive igneous and metamorphic rocks [1]. Granodiorite and biotite gneiss are exposed a short distance south from the study site at the south end of Chubb Park at the Great Unconformity, located just south of the Trout Creek Bridge (Figure 2).

Figure 2. The Great Unconformity with the Cambrian Formation sitting on Proterozoic Basement Crustal Rock at the southern end of Chubb Park on the Chubb Park Fault.

Paleozoic sedimentary rocks overlie the Proterozoic crustal basement rocks unconformably: the Great Unconformity (Figure 2), on Limestone and Kaufmann ridges and in Chubb Park. The Paleozoic rocks of this area include, from oldest to youngest, the Cambrian Sawatch Quartzite; the Ordovician Manitou Dolomite, Harding Sandstone, and Fremont Dolomite; the Chaffee Formation (Devonian) Parting Sandstone Formation and the Dyer Dolomite member; the Mississippian Leadville Limestone; and the Pennsylvanian Belden and Minturn Formations. These beds grade upward east of Kaufman Ridge and north of Chubb Park into the Maroon Formation. The Cambrian Sawatch Quartzite pinches out south of Limestone Ridge [2]. The highly pure Leadville Limestone was mined just south of the study site, in the past, at the Newett Quarries (Figure 3) which lie high up at the southern end of Limestone Ridge on the west side of the Trout Creek bridge. A warm water spring lies just north of the Trout Creek Bridge in Trout Creek at approximately the exposed contact of the Cambrian Sawatch Quartzite and the basement Granodiorite formations at N 38 degrees, 51.519 minutes. The Belden Shale, the formation in which the study site lies, and the lower Minturn Formation are the upper-most formations of the Paleozoic exposed in the area of the study site, underlying the sparsely conifer-forested, gentle hills of southern Chubb Park (Figure 1).

Figure 3. The Newett Quarries, a mile south of the study site on the east-facing slopes of Limestone Ridge.

The study site is within the intersection of three major tectonic features: the Rio Grande Rift, the Colorado Mineral Belt, and the Central Colorado Trough [3]. Rocks in this area have repeatedly been structurally deformed through time, and the Kaufman Ridge Anticline and Chubb Park Syncline are significant factors in this deformation. Chubb Park, containing the study site, is flanked on the west by a forested dipping slope of Mississippian Leadville Limestone and on the east immediately by forested slopes of dipping Minturn strata. Here, there have been a wide variety of geologic processes at play: plutonism and metamorphism forming and modifying the underlying Meso- and Paleoproterozoic crustal rock, marine sedimentation in the Paleozoic forming the Paleozoic layering (including the Belden, in which the study site lies) here exposed, northern Rio Grande rifting and associated mountain and basin development in the middle to late Tertiary contributing to and re-activating local faults and causing additional deformation of the study site area [4], glaciation and catastrophic flooding in the Pleistocene contributing to more recent significant surficial shaping of the study site area, and post-glacial sedimentation in the Holocene adding young-stream channel and overbank erosion and alluvium sediment in the study site area. Possibly the most striking geologic feature in this region is the Rio Grande Rift, a major continental rift zone with the Upper Arkansas River Basin just to the west being a major axial basin of the rift. The Rio Grande Rift is a zone of crustal spreading that extends south into Mexico [5] and north as far as southern Wyoming [6,7]. Just to the east of our study site, the Kaufman Ridge forms the crest of the east horst of the Rio Grande Rift (Figure 4).

Figure 4. Kaufman Ridge Anticline/Chubb Park Syncline Plunge at a segment of the Mosquito–Weston fault.

Geologic History

The North American Plates slid over several ancient plates, pushing up the North American Cordillera, the great belt of mountains from Alaska to Panama. The Ancient Rocky Mountains (ARM) resulted from one of these past North American Plate collisions—a collision with the South American/African Plate in Pennsylvanian time, known as the Ouchita-Marathon Orogeny, in the late Mississippian through early Permian period.

The ARM began eroding in Late Paleozoic and the erosion extended through the early Mesozoic timeframe. As the ARM eroded, thousands of meters of extensive sedimentary deposits were shed into the surrounding basins, including the Central Colorado Basin, and these remains formed the late Pennsylvanian/Permian rock units of the Paleozoic that are located above the Belden Shale unit containing the study site. By the end of the Permian period of the Paleozoic, the Ouchita-Marathon Uplift was completely eroded away, leaving only low hills and plains.

In the most recent tectonic past, the most important overridden plate was the Farallon Plate [4]. It was the largest seabed oceanic plate to plunge under the North American Plate and extended from, and including, today's Juan de Fuca Plate on the north through the Cocos Plate on the south, and ensuing subduction, with the convergence of the Farallon Plate and the North American Plate, began the Sevier Orogeny, known as having a second phase called the Larimide Orogeny, that started in the late Jurassic and continued into the Eocene. These two remnants of the Farallon Plate, the Juan de Fuca and Cocos, where the continental North American Plate has not overridden the eastern Pacific spreading zone (known as the Farallon-Pacific Ridge), still subduct normally under the western-advancing North American Plate today.

The Southern Rockies of southern Montana, Wyoming, Colorado, and northern New Mexico, called the Foreland Ranges, lie some 960–1600 km (600–1000 miles) inland from the west edge of the North American Plate. They occur unusually deep in the continental interior, so they are not the result of normal oceanic/continental plate subduction, nor do ancient continental and terrane collisions explain these mountains [4]. They started to rise with the beginning of the Sevier Orogeny after terrane collisions ceased and flat subduction of the Farallon Plate, without magma generation due to the slight angle of subduction, penetrated the plate far inland under the study site to well east under the Great Plains of North America, generating a great mountain building episode that created the

Southern Rocky Mountains and the Colorado Plateau, raising the region of the study site. The uplifted cores of these mountains are made of Proterozoic rock and are considered to be a basement-cored uplift. The Foreland Ranges are large wedges of basement rock squeezed up by colossal sideways pressure. They rose along ramp-like thrust faults, thrust up and over rocks below. Colorado and Wyoming were squeezed to 4/5ths their original widths [4]. The ranges and faults line up mostly north-to-south and northwest-to-southeast, as we observe in the study site area today. Massive sideways pressures of the Sevier into and through the Larimide compressed the continental basement and squeezed up the Southern Rocky Mountains and the Foreland Ranges.

The Farallon Plate subducted along an 800 km (500 mile) wide zone, southern Montana to northern New Mexico, powering the Sevier/Larimide Orogeny. This wide zone was probably an oceanic plateau of vast quantities of lighter basaltic volcanic rock vented onto the seabed up to 30 km (20 miles) thick. The buoyancy of the plateau of this much thicker material floated the plate upward in the mantle, so it slid flat beneath the continent as a great arch, applying intense pressures as it scraped the western region of the North American Plate above [4]. The Larimide Orogeny ended as the oceanic plateau portion of the Farallon Plate slid far to the east to underneath the Great Plains, allowing the Farallon Plate to bend back to normal subduction to the west. This caused volcanoes re-awakening in the western interior of the North American Plate with a vengeance during the Tertiary time period, including volcanic complexes in this region—Buffalo Peaks, the Aetna Caldera, the Grizzly Caldera, the Salida Volcanic Complex, the Nathrop Volcanic Complex, and the Guffey Volcanic Complex, among others. Flat subduction may have been the cause for such violent volcanism.

As the Farallon Plate slid flat during the Orogeny, great pressures may have squeezed quantities of seawater into the lower continental crust above. When the Farallon Plate angled back down, inflowing soft mantle above the plate began to melt by depressurization and, also, the water lowered the melting point in the mantle. As fresh magma entered the hydrated crust above, it could have expanded and exploded to up to 750 times its original volume.

Exhumation of the Southern Rocky Mountains from this deep Tertiary volcanic burial followed [4]. As the Larimide Orogeny subsided, erosion began to tear down the Foreland Ranges and violent volcanic activity further buried them. Rivers began to dig down, removing the covering debris. The soaring mountains of the study site region may owe as much to exhumation as to original uplift. The exhumation was thought to have several possible causes. One of the causes was the death of the Farallon Plate. The North American Plate overtopped the Farallon–Pacific Ridge from which the Farallon Plate grew and slid east, eliminating the plate's source and energy in the Eocene to Oligocene. Westward movement of the North American Plate over the now-dead Farallon Plate broke it up. With no eastward spreading of the Farallon–Pacific Ridge, subduction and plate movement ended. When the detached, inactive Farallon Plate cracked apart into several fragments, the pieces sinking into the mantle opened gaps through which hot mantle rocks and magma rose. As the western gaps in the disintegrating Farallon Plate opened more, additional hot mantle rock welled up under the Southern Rocky Mountains to push them up. A severely tilted fragment of the Farallon Plate under the Southern Rockies and the study site region caused the tensional forces that split the crust into the Rio Grande Rift, with its associated horst uplifts, and caused mantle depressurization to create the magma flow for the Front Range Uplift and other regional volcanism under the Southern Rocky Mountain region.

Additional possible causes include passive uplift, active uplift, and climate change. As rivers excavate, the crust floats upward, steepening and promoting further excavation. Since the Earth's crust floats buoyantly on the denser rock of the mantle, removing weight in a region will cause the region to float higher, creating passive uplift. The hot buoyant mantle beneath the Southern Rockies could have raised the region further, causing active uplift of the Southern Rockies during the last mountain building period. The American west became cooler and more arid after the Larimide, creating more focused and higher intensity storms. Mountain valley glaciers formed and melted with much more snow in this cooler period of climate change, leading to massive glacial erosion during glacial advance and massive flooding during re-warming and glacial receding. This has all resulted in more erosion power for the rivers in the region

The Southern Rockies today are still stretching east-to-west along the Rio Grande Rift in the study site area, caused by the pressure of the diving Farallon Plate fragment and upwelling hot mantle fluids, at least partly accounting for the continued hydrothermal flow in this region.

During the Exhumation, rivers like the North Platte, South Platte, and the Arkansas in and around the study site area carved out deep valleys like the Colorado Piedmont and Cheyenne Tableland regions [4]. A great ramp of tablelands rises out of Nebraska and Kansas to meet the Front Range at over 2013 m (7000 feet) in Colorado and southern Wyoming. The ramp consists of sand, volcanic ash, and gravel, sloped high against the Rockies and capped by the Ogallala Formation, and is known as the Rocky Mountain Sub-summit Surface. This broad bench-like surface resting about halfway up the face of the Front Range of the Rocky Mountains (like a step) was once continuous with the former Great Plains, until the Exhumation carved the cavernous bowl—the Colorado Piedmont.

Structure

The study site area has experienced numerous episodes of structural deformation. Most of the structural features in this area of study are oriented northwest-southeast or are perpendicular to the northwest-southeast features. The northwest-southeast features formed at different times from the Proterozoic to the Tertiary.

The northwest-southeast running faults show no evidence of movement during the Paleozoic, when the study site was deposited in the Belden. The compressive forces of the late Cretaceous to early Tertiary Larimide Orogeny may have formed most of the northwest-southeast faults and folds of this study area. Most of these faults terminate in the north against the Pony Park/Salt Creek east-west fault systems just north of the study site, indicating that the east-west systems were reactivated during and after the Larimide. In the study site, the Mosquito–Weston Fault (also named the Trout Creek Fault) is an up-to-the-east fault (the Kaufman Anticline), and a large north-plunging syncline (the Chubb Park Syncline) is located immediately west of the Mosquito–Weston Fault and contains the study site (Figure 4). The fold axes here are parallel to the fault. Similar axes are found in the faults bounding the Upper Arkansas Valley, indicating that the faults may be related to the opening of the Rio Grande Rift graben by the Oligocene, Neogene, and younger rift activity [8]. These folds do not offset any Quaternary surface deposits, indicating that the faults may not have undergone any significant movements since Quaternary deposition.

The most prominent structure in the study site area is the near vertical to steep, east-dipping north-northwest trending reverse Mosquito–Weston Fault, with the west block thrown down (the Chubb Park Syncline) relative to the east (the Kaufman Anticline) (Figure 4). It offsets Paleozoic strata by up to 850 meters. A lesser fault, the Chubb Park Fault, lies just to the west of the Mosquito–Weston Fault [8], paralleling it and forming the eastern boundary of the study site (Figure 5). Cambrian to Mississippian sedimentary rock layers are more faulted than the overlying Pennsylvanian layers, containing the Belden Shale that are folded above the Paleozoic faults, indicating that the Pennsylvanian and Permian rocks may not have been consolidated during some of the deforming activities at the at the study site. The north-northwest orientation of the Mosquito–Weston Fault [9] parallels the strike of the main Proterozoic faults [10,11] and runs through the area of the study site with numerous small faults scattered throughout. The latest slip in this fault system postdates deposition of the Belden Shale of the study site.

Figure 5. The Chubb Park Fault in the foreground, with the Kaufman Ridge Anticline in the background and the east side of the Chubb Park Syncline in-between.

The main tectonic events that influenced the sedimentation of the study site area are the Sawatch Uplift [12], the ancestral Front Range Uplift [13], the ancestral Uncompaghre Uplift [12], and the Central Colorado Trough [12] that ran northwest between the ancestral Uncompaghre and Front Range uplifts. During the period of 76–36 Ma, sedimentary, plutonic, and metamorphic rocks were uplifted, and the Central Colorado Trough became a source for early Tertiary sediment. Regionally tilted fault block dips of 16–21 degrees exhibit a consistent north-northwest strike that are not likely to occur in a depositional environment, so they may be the result of study site area tectonic tilting as a result of subsidence of the Rio Grande Rift to the west in the Upper Arkansas Valley (observed tilts correspond with the average structural tilt direction in the Upper Arkansas axial basin of the Rio Grande Rift [14]). The numerous northwest and north-northwest high angle faults down-to-the-west are the result of rift tectonics with displacements of 10s to 100s of feet [15].

The Kaufman Anticline and Chubb Park Syncline folds around the study site form a large-scale, anticline–syncline pair (Figure 4), deforming the Cambrian to Mississippian sedimentary sequence with medium-scale folds that deform the Pennsylvanian above (containing the study site). The large-scale, basement-cored Kaufman Anticline (Cambrian to Mississippian over the granodiorite core) plunges northwest through the study site area, following the Mosquito–Weston Fault. The large-scale Chubb Park Syncline [16] trends north from Limestone Ridge through Chubb Park (named the Pony Spring Syncline by DeVoto) (Figure 1). In Chubb Park, the Chubb Park Syncline contains the Belden Shale trends and plunges north-northwest and parallels the west side of the Mosquito–Weston Fault (the southern-most part of DeVoto's Pony Spring Syncline) just to the west of the fault. The syncline may be the result of a slip on the Mosquito–Weston Fault (Figure 4). This slip activity exposed the Belden Shale Formation, containing the study site at its base, above the base of the west upslope of the syncline on the east side of Limestone Ridge. Although poorly, this location has exposed the lower Belden study site to later downhill overbank sheet and stream channel erosion (a deep, young Holocene stream channel now runs straight through the study site), eroding into the exposed Belden and scattering fossil wood fragments lower on the west side of the syncline downhill toward the east and the Chubb Park Fault.

The Mosquito–Weston Fault was active during the Pennsylvanian event that produced the ARM/Sawatch Anticline Uplift and the Central Colorado Trough. The Pony Spring Fault on Limestone Ridge, just north of the study site, is evidence of Larimide deformation [17]. The Chubb Park Syncline and faults do deform and expose Proterozoic and lower Paleozoic rocks (Figure 6) and are related to the Kaufman Ridge Anticline to the east.

Figure 6. Cambrian through Ordovician Formations exposed by the Chubb Park Fault at the southern end of Chubb Park.

The structure of the area of the study site itself is complex, and poor exposure complicates efforts to understand it. The sequence of Cambrian through Mississippian rock layers was deposited over the region during a time of repeated rise and fall of water levels and/or episodes of regional uplift/subsidence. During the Late Paleozoic, this area was within the Central Colorado Trough depositional region. At Pennsylvanian time, during the Belden Formation deposition, the Central Colorado Trough received a thick sequence of clastic and carbonate rocks. Currently, at the study site, the Pennsylvanian begins with marine deposits including the Trout Creek fossil locality at the base that is part of the thick sequence, and grades upward to a continental sequence. A series of north-south trending down-to-the-west high angle reverse/thrust faults developed between the Elkhorn Thrust (to the east in South Park) and the Sawatch Uplift (to the west), one being the Mosquito–Weston Fault at our study site. It contains several north-northwest to south-southeast trending sub-faults, with hundreds to thousands of feet of displacement. The fault is linear, indicating it is a high-angle reverse fault [17]. The Mosquito–Weston Fault is offset by the Salt Creek and Pony Park faults to the north of our Study site. The hanging-wall anticline and footwall syncline occur along the Mosquito–Weston Fault (Figure 4). South of the Salt Creek Fault, in the study site area, the pre-Tertiary deposits are deformed by the north-northwest to south-southeast trending faults and folds, so dips are typically to the east-northeast and west-southwest.

The Kaufman Ridge just to the east of our study site is a Larimide-age faulted anticline that trends north-south and plunges to the north. Proterozoic rocks crop out in the axis and Paleozoic rocks flank the ridge. Several down-to-the-west, high angle reverse faults cut the west side of

Kaufman Ridge and the Chubb Park Syncline folds the strata in Chubb Park at the study site. In this area, the Proterozoic rock core of Kaufman Ridge is poorly exposed.

Stratigraphy

Proterozoic Rock Units

Proterozoic rocks around the study site are primarily igneous and some metamorphosed igneous rock, including Paleoproterozoic and Mesoproterozoic granodiorite and younger stocks and dikes of granite. They form the core and structural basement of the Kaufman Ridge Anticline and Chubb Park Syncline. The oldest rocks occur as xenoliths in the large granodiorite pluton; blocks of biotite gneiss where the sediments that were formed into the biotite gneiss were deposited in the late Paleoproterozoic age. The granodiorite is dated in the Cameron Mountain Quadrangle as Paleo- to Mesoproterozoic age.

Paleoproterozoic is the main igneous rock in the area of the study site, forming a large pluton underlying the Paleozoic rocks of the area and outcropping at the very southern end of Chubb Park, just a mile south of the study site. It is a course to very course, grained, non-foliated to slightly foliated granodiorite, and what is exposed is the interior part of the pluton. In the area of the Mosquito–Weston (Trout Creek) Fault, the granodiorite is well foliated. The Proterozoic granite occurs as stocks and dikes in the area of the study site as intrusions in the older granodiorite. These stocks and dikes are thought to represent the uppermost portions of a granite or quartz monzonite body at greater depth.

Paleozoic Rock Units

The Paleozoic rocks in this region average around 600 m (2000 feet) in thickness. The Sawatch Quartzite (Upper Cambrian) forms the base of the Paleozoic sequence, resting on the Proterozoic basement rocks as the major Great Unconformity. The sequence, in ascending order from the Proterozoic contact, is the Sawatch Quartzite followed by the Manitou Limestone (Lower Ordovician), Harding Quartzite (Middle Ordovician), Fremont Dolomite (Middle to Upper Ordovician), the Chaffee Group (Upper Devonian) consisting of the Parting Quartzite Lower Member and the Dyer Dolomite Upper Member, the Leadville Limestone (Lower Mississippian), the Belden Shale Formation (Lower Pennsylvanian), and the Lower Minturn Formation (Middle Pennsylvanian). Most of the units above are separated by disconformities of what are thought to be long periods of time with no deposition or cycles of deposition and erosion.

The silicification of the Paleozoic rocks at and surrounding the study site is of particular interest due to the extent of silicification [18,19]. Not only are the fossils of the study site in the Belden well-preserved silicified wood [2], but all the Paleozoic formations from the Cambrian Sawatch, up to and including the Belden, exhibit at least some silicification. The Cambrian Sawatch is a well-sorted, tightly silica-cemented orthoquartzite with silica-cemented breccia fragments of quartzite. The Manitou Limestone contains chert nodules, lenses, and beds, as well as silicified beds of laminated chert that replaced dolomite and, in some places, formed the entire unit. The Harding Quartzite is a well-sorted, silica-cemented, dense orthoquartzite completely cemented by silica, exhibiting the conchoidal fracturing of a quartzite, along with angular breccia fragments of quartzite and, locally, basal breccia zones of chert clasts that appear to be related to faulting [15]. The Fremont Dolomite has black chert nodules irregularly distributed through the dolomite [18]. The Parting Quartzite is fine-grained, dense, flinty silica-cemented orthoquartzite with lenticular shale and laminated chert interbeds that are conchoidal-fracturing rock. The Dyer Dolomite contains some lenticular interbeds of shale and laminated chert, and some chert layers are interbedded with bulbous zones of altered chert breccia that appear to be formed by solution and collapse [8]. The Leadville Limestone, just below the Belden and the study site, is most interesting in relation to silicification. It contains laminated chert nodules and lenticular chert beds at some stratigraphic locations and, locally, chert occurs as irregular replacement masses, as well as thin silica-cemented orthoquartzite beds occurring at the top of the unit east of Limestone Ridge (the area of the study site). The thickness of the Leadville unit is noted to vary, possibly due to post-lithification solution and from volume reduction due to solution and silicification of limestone. Wallace and Keller [19} note that a major hot water solution event at a time after lithification of the Leadville formed caves and solution breccias in the upper portion of the unit. This solution event may be related to the silicification in the Leadville. Wallace and Keller [19} also note that, during Pennsylvanian time, the Central Colorado Trough received a thick sequence of clastic and carbonate rocks. In the study site area, in the central part of the Central Colorado Trough, the Pennsylvanian sequence begins with marine deposits, like the Trout Creek lycopsid fossil site, at the base of the Belden, and grades upward into a continental sequence where tongues of continental deposits form wedges in the marine strata.

Reed and Ellis [3] point out that the upper mantle in this entire region around the study site was heated and injected with hot water (hydrothermal flow) and other volatile components both during the Larimide and post-Larimide tectonic, and volcanic activities were caused by the flat-subduction and break-apart of the Farallon Plate [4]. Areas of weakness and faults/fractures acted as conduits for heat and hydrothermal and magma flows that fed intrusions from the mantle. One zone of weakness and warm viscous mantle was approximately along the Colorado Mineral Belt and another was the Rio Grande Rift. As the rift opened, creating faults and fractures in the surrounding rocks, the horsts on its flanks rose partly from the outflow of hot materials at depth and from warming of the surrounding rocks. Even after subsidence of the tectonic uplifting of the Rio Grande Rift and the hydrothermal and magma flows, we still have significant hydrothermal activity remaining in the greater study site area, that is still high in dissolved silica content, indicating that rock alteration is still occurring at depth. Approximately a mile south of the study site, there is a hot water spring still flowing from depth into Trout Creek and about 16 km (10 miles) to the northeast we have a significant set of geothermal hot springs flowing at Hartsel into the South Fork of the South Platte River. To the west and southwest, there is major geothermal hot spring activity from the Cottonwood Hot Springs just west of Buena Vista to the Mt. Princeton Hot Springs just west of Nathrop and the Poncha Hot Springs west of Salida. A highly permeable underground sand and gravel hydrothermal reservoir has been located in the Upper Arkansas Valley near Nathrop [20], a post-Larimide extensional feature. All of these sites may be remnants of significant hydrothermal flow activity opened up in this region by the Rio Grande Rift, and may be at least part of the cause and source of the large amount of hydrothermal replacement and silicification found at and around the study site.

Description of Rock Units in the Area (From Youngest to Oldest)

A generalized stratigraphy for the study site is given below, with detailed descriptions for each formation (Figure 7).

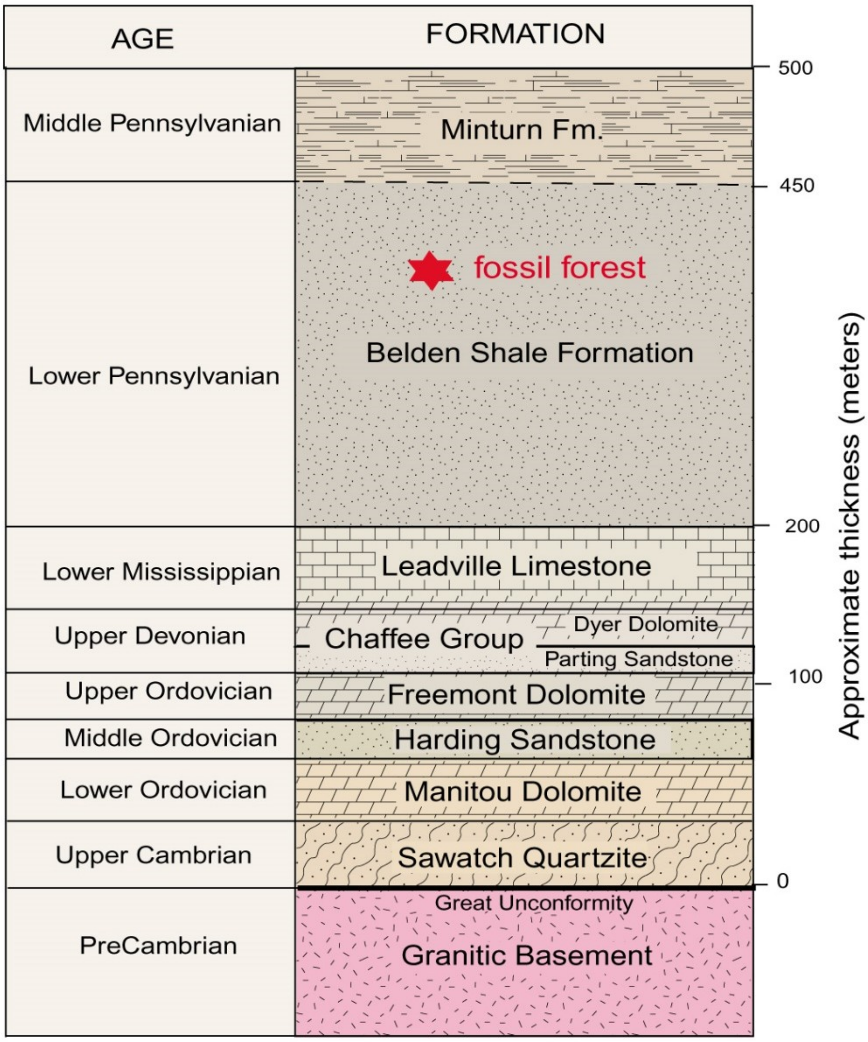

Figure 7. Generalized stratigraphy for the Trout Creek lycopsid fossil locality.

Minturn Formation Group (Middle Pennsylvanian)

Some of the Minturn Formation Group is exposed in Chubb Park, but no complete or undeformed sections are visible. The Group is thought to be about 1814 m (5950 feet) thick, with three recognized member units: the Upper Member, at about 1524 m (5000 feet thick); the Coffman Member, at around 213+ m (700+ feet) thick; and the Lower Member, at around 60 m (200 feet) thick. The Group has a number of rock types represented, including conglomerate, sandstone, siltstone, shale, dolomite, limestone, gypsum, and probably halite and other evaporate minerals in the subsurface. A lateral evaporite body (facies) of primarily gypsum and gypsum shale exists in the Upper Member.

Upper Minturn Member (Middle Pennsylvanian)

This formation consists of sandstone, shale, siltstone, limestone, calcareous shale, and gypsum shale and is about 899 m (2950 ft) thick. Sandstone layers can be thick and are made of mostly fine-grained feldspar and mica with plant debris, mud chips, and limestone pebbles that are reddish brown, tan, gray, or greenish in color. Sedimentary structures contain mud cracks, ripple marks, rain drop impressions, groove marks, and bioturbation. Limestone beds are usually gray and up to a foot thick. The upper 322 m (200 ft) of this upper member consists of calcareous gypsum shale, the thickest throughout this area and the most common rock type exposed at the surface. The lower 625 m (2050 ft) of the Upper Member contains the above beds, as well as beds of limestone, gypsum, and gypsum shale. The limestone beds are up to about 1 m (3 ft) in thickness, gray, and weather to a light gray or brown. Sandstone and siltstone beds are fine-grained, laminated and fissile, quartz-rich, tan, gray, pale red in color, and usually less than 0.3 m (1 ft) thick.

An evaporate facies, a lateral sediment body, in the upper member, crops out in the study site area. It contains gray gypsum and calcareous shale along with some sandstone, gypsum, and limestone. Halite is present to the east and may be present in the subsurface at the study site. The tan, gray, or pale red sandstone layers are thin, fine-grained, and rich in quartz, and the limestone layers are dark to medium gray and black with algal laminae and mud cracks, or course and vuggy and brecciated. The gypsum beds are gray, black, or white, and no intact outcrops are visible, but loose pieces of gypsum and small sinkholes are found east of the Mosquito–Weston fault and south of Pony Park, just to the north and east of the study site. The facies s deformed and faulted, so the thickness is not known but thought to exceed 300 m (1000 ft). The facies erodes and creates some vegetated valleys with light-colored soils.

Coffman Member (Middle Pennsylvanian)

This formation contains conglomerate, sandstone, shale, and dolomite/limestone. The sandstones and conglomerates are mostly tan, along with some gray, reddish brown, and greenish brown layers, with mostly feldspars and mica along with some quartz-rich layers. Quartzite and black chert clasts are common near the base of the unit. Only the lower portion of the Coffman is exposed at the study site area with around 45 m (150 ft) of exposure toward the north, but is estimated to be up to around 200 m (700 ft) thick. It weathers to form small ridges and hogbacks that have conifers growing on them.

Lower Minturn Member (Middle Pennsylvanian)

This formation consists of sandstone and shale with lesser amounts of siltstone, limestone, and dolomite. The sandstone is a gray color and weathers to shades of tan, brown, reddish-brown, and orangish-tan. Some of the sandstone beds contain plant debris, petrified wood, and shale rip-up. There are minor exposures on the east side of the study site across and just south of the intersection of CR 309 with the Lenhardy Cutoff (FS 376). Fine to coarse grains are quartz, feldspar, and mica. Beds run about 7.5–15 cm (three to six inches) thick, are fining-upward sequences, and form small ridges with conifer trees, hogbacks, and separating valleys with shale below that is dark gray to black, fissile, and clay rich, that weathers to reddish brown soil, making gentle grassy slopes. This unit is bounded on the east by the Mosquito–Weston Fault and is around 60 m (200 ft) thick. The contact with the Belden Shale Formation is conforming and transitional, at the base of a ridge-forming sandstone deposit where greenish-gray shale and sandstone start to dominate [21].

Belden Shale Formation (Lower Pennsylvanian)

The Belden Shale is poorly exposed in the study site because of its weathering style and is the formation in which the study site resides. It consists of dark gray, brownish gray, and black shale, limestone, and siltstone. The shale nearer to the top of the formation is thin-bedded and highly fissile with some carbonaceous shale beds in Chubb Park. White calcite veining is common, sometimes obscuring the fossils within. At the study site and around Trout Creek Pass, silicified Lycopsid wood, bark, and tree parts are well preserved. The thickness of the Belden Shale is estimated to be 260 m (850 ft) but the top of the unit has been eroded. Zones of black shale are as thick as 18 m (60 et) in beds of olive-drab siltstone. Bituminous shale is also common. The Belden Shale reaches a maximum thickness of 520 m (1700 ft) a short distance northeast from the study site at Trout Creek Pass [9,22]. The lower Belden Shale contact with the Leadville Limestone is disconforming.

Leadville Limestone (Lower Mississippian)

This formation consists of massive blue-gray to gray, fine-grained dolomite, that can locally be dark-gray to black. Its weathered surfaces are often abrasive and pitted and it is resistant to erosion. Black and some white chert nodules and lenticular chert beds occur, and red chert occurs as replacement at the top of the unit. A replacement solution event occurred after lithification formed caves and breccias in the upper part of this unit. The breccias are made of dolomite clasts of limestone and red and yellowish-orange chert. In some places, the rock is recrystallized into black and white bands a few millimeters thick and has been named zebra rock. This unit's thickness reaches over 60 m (200 ft) in the area just south of the study site. The variation in thickness may result from the solution of limestone after lithification and reduction resulting from solution and silicification of the limestone. The Leadville unit forms large dipping slopes inclined to the northeast with terraces on top. The base contact of this unit with the Dyer Dolomite is disconforming.

The study site lies in the lower Belden Shale Formation, just over a mile north of the very pure exposure of Leadville Limestone on the southeast slopes of Limestone Ridge at the old Newett Limestone Quarry (Figure 3) where this pure limestone (low in content of magnesium and other impurities) was quarried and transported by the Colorado Midland RR to Leadville, CO, for use as a smelter flux. There were several individual open-cut quarries in the Leadville Limestone of southeastern Limestone Ridge that are still visible from the study site.

Chaffee Group (Upper Devonian)

The Chaffee Formation is exposed on Limestone Ridge, south of the study site and just north of the US Highway 24/285 crossing of Trout Creek. It is composed of dolomite, limestone, sandstone, and shale. The Group includes the upper Dyer Dolomite member and the lower Parting Formation [16]. It rests disconformably on the Fremont Dolomite Formation below. The Chaffee Group is resistant to weathering, so it forms slopes between the massive weathering Leadville Limestone Formation above and the massive Fremont Dolomite Formation below. The total thickness of the Group is estimated to be 40–46 m (130–150 ft) thick on Limestone Ridge.

Dyer Dolomite Member (Upper Devonian)

The Dyer Dolomite is medium to dark gray in color and weathers light gray with a relatively soft, smooth surface. Yellowish to tan chert breccias are common, with the chert clasts reaching up to several meters in diameter in a chert matrix. The lower part of the unit is light gray crystalline vuggy limestone. The upper part of the unit consists of thin-bedded to massive dense laminated limestone layers that are resistant to weathering. The formation runs 27–40m (90–130 ft) in thickness in this area on the Limestone ridge. The base contact with the Parting unit is gradual and conformable.

Parting Sandstone Formation (Upper Devonian)

Much of the Parting Unit is light purple to tan, poorly sorted quartz and dolomite sandstone. The sand grains range from fine to coarse. Beds are thin and wavy. It forms small ridges and benches on dipping slopes. It is less resistant to weathering than the surrounding dolomites and dense orthoquartzite. The base shale beds are red in color. The unit runs 12–18 m (40–60 ft) thick in the area of the study site. The base contact with the Fremont Dolomite is a major disconformity at the Ordovician/Devonian boundary.

Fremont Dolomite (Upper Ordovician)

The Fremont Dolomite Unit is composed of gray medium-crystalline and sandy dolomite that is dark to light gray and weathers to a yellow-gray weathered surface that is rough with sharp ridges. It occurs as massive, several-foot-thick beds that are poorly preserved. There is a reddish-brown alteration at its base. Where the unit is exposed in the area of the study site, it forms cliffs and benches. The unit is rich in fossils, especially corals and brachiopods, and also contains widely distributed black chert nodules. The unit is around 23–30 m (75–100 ft) thick on Limestone Ridge and thins out to the north of the Trout Creek Pass. The contact with the Harding Sandstone below is disconforming.

Harding Sandstone (Middle Ordovician)

The Harding Sandstone is dense, completely silica-cemented quartz sandstone and considered an orthoquartzite. It consists of alternating beds of shale and sandstone, and the individual beds run thin. The color runs from a light greenish gray to a dark reddish-brown, rusty orange, or yellowish-brown. This unit forms small cliffs, ridges, and hogbacks between the less resistant Fremont and Manitou units. It is about 30 m (100 ft) in thickness in the Limestone Ridge area. The contact with the Manitou Dolomite is disconformable.

Manitou Dolomite (Lower Ordovician)

The Manitou Dolomite consists of light-to-dark gray to gray-brown and buff, medium to fine grained crystalline, massive to bedded dolomite, with rare beds of limestone. Weathered surfaces are light gray, chalky white, or brown. Outcrops are rough and pitted but not sharp like the Leadville Unit. The unit also has numerous silicified burrows with white chert. The lower part of the formation contains white, gray, and black nodules of chert. Chert is not as common in the upper portion of the unit. Silica may replace entire beds or partially replace haloes around fractures. The Manitou forms prominent high cliffs. It is 45–67 m (150–220 ft) thick on the Limestone Ridge. The Manitou contact with the Sawatch Quartzite is disconformable.

Sawatch Quartzite (Upper Cambrian)

The Sawatch Quartzite is the oldest Paleozoic unit in the area of the study site. It lies over the Paleoproterzoic granodiorite. The Sawatch Quartzite is fine to medium grained, well sorted silica-cemented orthoquartzite, consisting of white to pale pink quartz, sand-sized grains interbedded with reddish-purple, fine-grained quartz sandstone. The unit thins from north to south and is about 3 m (10 ft) thick around the Lenhardy Cutoff at the study site. The unit is a cliff-maker resistant to erosion that forms small cliffs and ridges. The lower contact of the unit is directly on the eroded surface of the Proterozoic and is a smooth surface. This contact is a major unconformity—the Great Unconformity.

Proterozoic Rock Units

Granodiorite (Paleoproterozoic)

Granodiorite is the major bedrock of the study site area. It is part of a large intrusive body that is exposed from the western edge of the Sawatch Mountain Range to the southern edge of the Front Range [23]. The granodiorite is medium to light gray in color, coarse to very coarse grained, and massive to moderately foliated. It can be pinkish-gray on unweathered surfaces. It contains the minerals plagioclase, orthoclase, quartz, biotite mica, and hornblende. The alignment of the biotite mica is what defines the foliation. In some places, biotite has been altered to chlorite and the plagioclase (approximately 35% of the content of the rock mass) is white and partially altered to clay minerals. The age is determined to be 1.672 +/−5 Ma [1], as dated in the Cameron Mountain Quadrangle to the south of the study site. The granodiorite of the study site area represents the interior, less foliated portion of the pluton. Around the Mosquito–Weston Fault, the granodiorite is well foliated.

Biotite Gneiss (Paleoproterozoic)

Biotite Gneiss is the oldest rock in the study site area and occurs only as xenoliths in the large granodiorite pluton. One xenolith block is exposed in the road cut along US Highway 24/285 in the vicinity of the bridge over Trout Creek at the southern mouth of Chubb Park, and is dark gray to black, medium grained, and consists of biotite, quartz, plagioclase, orthoclase, and hornblende. The plagioclase is twice the percentage content of the orthoclase in the rock mass. This block is well foliated at its margins and poorly foliated in the center of the block. Narrow dikes of the granodiorite intrude near the contact with the biotite gneiss. Small pieces of the biotite gneiss do occur occasionally as float in the granodiorite. The sedimentary rock from which the biotite gneiss was formed was deposited in the interval of 1.75 to 1.95 Ga [24,25]. The biotite gneiss is schistose where the biotite is more than 50% of the rock mass.

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